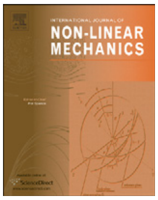
International Journal of Non-Linear Mechanics 46 (2011) 470–477

Contents lists available at ScienceDirect

International Journal of Non-Linear Mechanics

journal homepage: www.elsevier.com/locate/nlm



Performance evaluation of shape-memory-alloy superelastic behavior to control a stay cable in cable-stayed bridges

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A R T I C L E I N F O

Article history:
Received 8 July 2009
Received in revised form
23 November 2010
Accepted 1 December 2010

Keywords:
Shape-memory alloys
Stay cable
Superelastic
Dampers

A B S T R A C T

This paper focuses on introducing and investigating the performance of a new passive control device for stay cable in cable-stayed bridges made with shape-memory alloys (SMA). The superelasticity and damping capability of SMA is sought in this study to develop a supplementary energy dissipation device for stay cable. A linear model of a sag cable and a one-dimensional constitutive model for the SMA are used. The problem of the optimal design of the device is studied. In the optimization problem, an energy criterion associated with the concept of optimal performance of the hysteretic connection is used. The maximum dissipation energy depends on the cross-sectional area, the length, and the location of the SMA on the cable. The effectiveness of the SMA damper in controlling the cable displacement is assessed. Furthermore, a study is conducted to determine the sensitivity of the cable response to the properties of the SMA device. The comparison between the SMA damper and a more classical passive control energy dissipation device, i.e., the tuned mass damper (TMD), is carried out. The numerical results show the effectiveness of the SMA damper to damp the high free vibration and the harmonic vibration better than an optimal TMD.

1. Introduction

Over the last few decades, cable-stayed bridges have attracted great interest because of their aesthetics, structural efficiency, and economy. This type of construction has become popular worldwide in recent years, largely due to the rapid progress in design methodology and construction technologies [26]. However, stay cables are critical structural components in these bridges. Owing to their large flexibility, relatively small mass and extremely low damping, stay cables have frequently exhibited large-amplitude vibrations under wind, wind–rain and support motion. Aerodynamic instability of stay cables with extremely large oscillation amplitude under specific rain and wind conditions has been observed in a number of cable-stayed bridges worldwide, and it is a conundrum to civil engineers [29,39]. Therefore, the mitigation of dynamic response quantities induced by environmental loads is of vital importance in terms of safety and serviceability [2,25].

In the past decade, cable vibration control techniques by means of passive countermeasures, including aerodynamic, mechanical and structural means, have been broadly investigated and successfully implemented [17]. In the meantime, researchers have also studied the active vibration control of cables by applying transverse force control and axial stiffness or tension (support motion) control [30,35].

A lot of researches have been conducted to investigate possible damping systems and to determine the optimal size of viscous dampers attached to cables for vibration control. Kovacs [15] was among the first to investigate the maximum attainable damping ratio for a taut cable with a viscous damper. Pachero et al. [3] proposed a "universal estimation curve" of normalized modal damping ratios versus normalized damper coefficient for a horizontal taut string model. This "universal estimation curve" is generalized by Cremona [5] for inclined cables by taking account of the sag-extensibility parameter. A transfer matrix formulation is developed by Xu et al. [40] to estimate the modal damping ratio of inclined cables attached with oil dampers. Main et al. [18] proposed an analytical formulation of a taut cable with an attached damper. Theoretical studies were also carried out to evaluate the increased damping level of a stay cable after installing passive viscous dampers [2]. It was found that there exists an optimum viscous coefficient of the damper by which the modal damping ratio of a stay cable can reach its maximum for a given mode of vibration. However, this passive device suffers from several drawbacks such as the modal damping ratio of the stay cable decreases rapidly when the viscous coefficient deviates from its optimal value. The use of a variable-orifice viscous damper and electrorheological or magnetorheological (ER/MR) fluid damper with semi-active control may be an alternative [38]. However, the semi-active control device is more complicated to implement.

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doi:10.1016/j.ijnonlinmec.2010.12.002

Another candidate that has a great potential for vibration control of stay cable subjected to wind and wind/rain loads is a superelastic shape-memory alloy (SMA) damper with the advantages of large damping capacity, self-centering ability, high fatigue-resistant performance and good corrosion resistance [21].

As a natural consequence of the microscopic behavior, at the macroscopic level shape-memory solids present the superelastic effect (the recovery of large deformations in loading–unloading cycles, occurring at sufficiently high temperatures) and the shape-memory effect (the recovery of large deformations by a combination of mechanical and thermal processes).

These unique properties enable SMA to be used as actuators, passive energy dissipators and dampers for civil structural control [14,1,11,32,31]. When integrated with civil structures, SMAs can be passive, semi-active, or active components to reduce damage caused by environmental impacts.

Using SMAs for passive structure control relies on the SMA's damping capacity, which represents its ability to dissipate vibration energy of structures subject to dynamic loading.

Several authors investigated the energy dissipation of widely used Nitinol superelastic SMA wires. Dolce and Cardone [23] studied superelastic Nitinol wires subjected to tension loading. They observed the dependence of the damping capacity on temperature, loading frequency and the number of loading cycles. Grandhi and Wolons [10] proposed using a complex modulus approach to characterize the damping capacity of superelastic SMA wires for convenient integration with structure dynamics. A superelastic SMA wire demonstrates the damping capacity not only under tension loading, but also under cyclic bending [20]. The numerical results showed that the energy dissipated by the superelastic SMA wire is highly sensitive to its diameter, i.e., the thicker the SMA wire, more energy is dissipated.

SMA energy dissipation devices have been seen in the forms of braces for framed structures [37], connection elements for columns [16], retrofitting devices for historic building [24] and dampers for simply supported bridges [28].

Recently, as large cross-sectional area SMA elements are becoming available, and studies on the properties of SMA bars have attracted more attentions [23,36]. As indicated in Ref. [36], the damping capacity of a martensite Nitinol bar under tension–compression cycles increases with increasing strain amplitude, but decreases with loading cycles and then reaches a stable minimum value. The optimization of the cross-sectional area and the length of the SMA device is presented in [22]. The dynamic performance of the device is evaluated by the steady-state response at the resonance point in order to focus on the damping effect. Analytical formulation utilizing the equivalent linearization approach successfully leads to the basic correlation between the hysteresis shape and the damping effect.

To explore the potentials of SMA based energy dissipation in passive structure control, this paper presents an approach to study the damping vibration of stay cables in a cable-stayed bridge by using a SMA energy dissipation devices with superelastic hysteresis. The first part of the paper presents the general three-dimensional equations of a stay cable subjected to external dynamic loading and controlled by a distribution of dampers in the transverse direction, detailing the hypothesis of the problem linearization. The second part of the paper focuses on three aspects: formulating a mathematical model of the cable with one SMA damper using a Galerkin approximation, verifying the feasibility of the SMA to control the stay cable, and optimizing the SMA device using numerical method. For this simulation a one-dimensional model for superelastic SMA [9] is considered. Finally, the third part of the paper, focuses on the comparison between the TMD and the SMA energy dissipation device to control the stay cable free and harmonic transverse vibration.

2. Dynamic equations formulation of a sag stay cable

A cable is a spatially distributed system, whose transversal dimensions are significantly smaller than longitudinal one. Stay cables have very low levels of inherent mechanical damping and the mechanisms associated with the observed large-amplitude vibrations are still not fully understood. This section has two goals; the first goal is to present the general three-dimensional equations off a stay cable subjected to external dynamic loading and controlled by a distribution of dampers in the transverse direction. The second goal is to introduce the hypothesis leading to the problem linearization; i.e., the assumption of a small sag and the uncoupling of the in-plane and out-of-plane behaviors.

We start considering a cable connecting two points denoted as *A* and *B* and placed to a distance *L*. The segment connecting *A* and *B* defines an angle θ versus horizontal axis. For the case of only body load, the cable configuration is planar and we indicate with *Axy* an orthogonal reference system defined within such a plane. The planar oscillations can occur in the transverse direction (y-axis) as shown in Fig. 1 and non-planar oscillations can occur in direction *Az*, so that *Axyz* forms a direct orthogonal frame.

The equations governing the static equilibrium of an inclined cable element subjected only to dead load (gravity) are

$$\begin{cases} \dfrac{\partial}{\partial s}\left[T\dfrac{dx}{ds}\right] = mg\sin\theta \\ \dfrac{\partial}{\partial s}\left[T\dfrac{dy}{ds}\right] = -mg\cos\theta \end{cases} \tag{1}$$

where s is the Lagrangian co-ordinate, T is the static cable tension, m is the mass of the cable per unit length, and g is the acceleration due to gravity.

A non-linear dynamic model of an inclined cable is built in the coordinate system (*Axyz*) by three coupled partial differential equations [13]:

$$\begin{cases} \dfrac{\partial}{\partial s}\left[(T+\tau)\left(\dfrac{dx}{ds}+\dfrac{\partial u}{\partial s}\right)\right]+F_x(x,t) = m\dfrac{\partial^2 u}{\partial t^2}+mg\sin\theta \\ \dfrac{\partial}{\partial s}\left[(T+\tau)\left(\dfrac{dy}{ds}+\dfrac{\partial v}{\partial s}\right)\right]+F_y(x,t)-\displaystyle\sum_{i=1}^{M} f_{c,i}(t)\delta(s-s_{c,i}) = m\dfrac{\partial^2 v}{\partial t^2}-mg\cos\theta \\ \dfrac{\partial}{\partial s}\left[(T+\tau)\dfrac{\partial w}{\partial s}\right]+F_z(x,t) = m\dfrac{\partial^2 w}{\partial t^2} \end{cases} \tag{2}$$

where τ is the dynamic cable tension; u, v and w are the cable dynamic displacement components in the x-, y- and z-directions, respectively, measured from the position of the static equilibrium

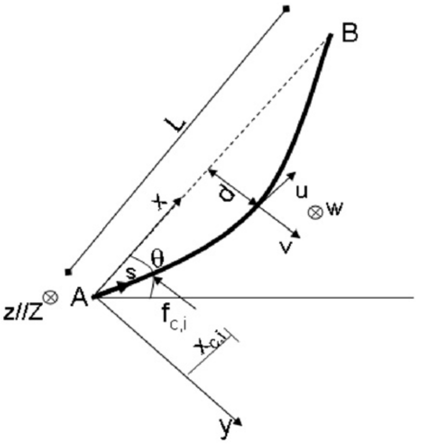

Fig. 1. Schematic diagram of an inclined stay cable.